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Tensor Polarizabilities of Magnetoelectric Particles on the Base of Strip-Line-Coupled Magnetostatic Wave Resonators

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Abstract

An electrodynamic description of bianisotropic particles on the base of strip-line-coupled magnetostatic wave (MSW) resonators is developed and analytical closed-form expressions for their tensor polarizabilities are obtained for an arbitrary direction of a magnetizing field and an arbitrary resonator shape. Numerical calculations are performed for a normally magnetized thin-ferrite-film disk resonator with a metal strip on its surface.

1. Introduction

Recently proposed composite non-reciprocal bianisotropic materials [1] represent ensembles of magnetized thin-ferrite-film magnetostatic wave resonators with surface metallization. Induced electric and magnetic dipole moments $\mathbf{p}_e$ and $\mathbf{p}_m$ of such artificial particles are related to the external electric and magnetic fields as

$$\mathbf{p}_e = \overleftrightarrow{\alpha}_{ee}\mathbf{E} + \overleftrightarrow{\alpha}_{em}\mathbf{H}\ , \qquad \mathbf{p}_m = \overleftrightarrow{\alpha}_{me}\mathbf{E} + \overleftrightarrow{\alpha}_{mm}\mathbf{H}\ , \tag{1}$$

where $\overleftrightarrow{\alpha}_{ee}$, $\overleftrightarrow{\alpha}_{em}$, $\overleftrightarrow{\alpha}_{me}$ and $\overleftrightarrow{\alpha}_{mm}$ are corresponding tensor polarizabilities. Although a nature and qualitative physical picture of magnetoelectric coupling in these elements is quite obvious and an experimental evidence of the effect has been obtained [2], the electrodynamic description of the particles and quantitative evaluation of magnetoelectric coupling till the present time has not been performed. In this paper we consider a thin-ferrite-film resonator with a linear metal strip of the width b on its surface, as shown in the Fig.1 for a disk resonator magnetized by the field H_0 in an arbitrary direction η. Dimensions of the resonator are much less than a wavelength in the surrounding media with the permittivity ε, so electric and magnetic fields in (1) can be assumed uniform and quasi-static. Magnetization of oscillation modes $\mathbf{m}_q$ for the type q and corresponding eigenfrequencies ω_q are supposed to be known, as well the ferromagnetic resonance linewidths ΔH_q. The approach is based on the earlier obtained solutions of self-consistent electrodynamic problems of the excitation of one-port [3] and two-port [4] MSW resonators. In this formulation, in particular, dipole moments of a particle, induced by an external magnetic field are found through a resonator high-frequency magnetization, which is determined taking into account the "back" influence of the current in the strip on this magnetization. Neglecting of this interaction results in the non-accurate determination of the polarizabilities $\overleftrightarrow{\alpha}_{em}$, $\overleftrightarrow{\alpha}_{mm}$ and their resonant frequency. Presented electrodynamic description of magnetoelectric particles enables to obtain constitutive relations for composite media in a closed form.

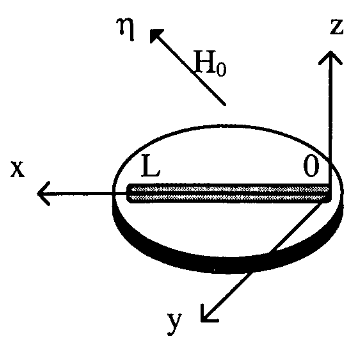

Fig. 1

2. Self-Consistent Electrodynamic Problem for $\tilde{\alpha}_{em}$ and $\tilde{\alpha}_{mm}$ Determination

Tensor polarizabilities $\tilde{\alpha}_{em}$ and $\tilde{\alpha}_{mm}$ are calculated in the assumption that $\mathbf{E} = 0$ in (1). Magnetization induced by a given magnetic field $\mathbf{H}$ is found as an expansion into the series of eigenmodes

$$\mathbf{M} = \sum_q c_q \mathbf{m}_q, \quad c_q = \varphi_q \int_V (\mathbf{H}+\mathbf{h}_\mu)\cdot \mathbf{m}_q^* dV \quad , \tag{2}$$

where $\varphi_q = -\dfrac{b_q}{\omega^2 - \omega_q^2 - i\omega_q^2 Q_q^{-1}}$, $b_q = \dfrac{i(\omega+\omega_q)\omega_M}{\Phi_q}$, $\Phi_q = \int_V [\mathbf{m}_q \times \mathbf{m}_q^*]_\eta \, dV$,

$Q_q = \dfrac{H_0}{2\Delta H_q}$, $\omega_M = \gamma\mu_0 M_0$, γ is the gyromagnetic ratio, μ_0 is the permeability of free space, M_0 is the saturation magnetization, and V is the resonator volume. The "back" influence of a strip current on the magnetization is taken into account by including the magnetic field $\mathbf{h}_\mu$ in (2), which can be found as a field of a transmission line excited by an equivalent given magnetic current $i\omega\mathbf{M}$

$$\mathbf{h}_\mu = c_\mu(x)\mathbf{H}_\mu^r + c_{-\mu}(x)\mathbf{H}_{-\mu}^r \ , \tag{3}$$

with

$$c_\mu(x) = -\frac{i\omega\omega_0}{N_\mu^r}\int_0^x dx \int_S (\mathbf{M}\cdot\mathbf{H}_{-\mu}^r)dS, \quad c_{-\mu}(x) = -\frac{i\omega\omega_0}{N_\mu^r}\int_x^L dx \int_S (\mathbf{M}\cdot\mathbf{H}_{-\mu}^r)dS$$

where $\mathbf{H}_\mu^r = \mathbf{H}_\mu + \Gamma_2 \mathbf{H}_{-\mu}$, $\mathbf{H}_{-\mu}^r = \mathbf{H}_{-\mu} + \Gamma_1 \mathbf{H}_\mu$, $N_\mu^r = (1-\Gamma_1\Gamma_2)N_\mu$, $\mathbf{H}_{\pm\mu} = \mathbf{H}_{\pm\mu 0}(y,z)\,exp(\mp i\beta x)$ is the magnetic field of a dominant wave in a strip-line (in the absence of ferrite) with the propagation constant β, N_μ is a normalization coefficient [4], Γ_1 and Γ_2 are the reflection coefficients for a strip current at $x = 0$ and $x = L$ ($\Gamma_1 = -1$ and $\Gamma_2 = -exp(-2i\beta L)$ for our case of an open transmission line), and S is the cross section of the line. The system of integral equations (2), (3), formulating a self-consistent electrodynamic problem, has the following solution for amplitudes of electromagnetic waves in the transmission line

$$c_\mu(x) = \left[\left(e^{i\beta x}-1\right) - \Gamma_1\left(e^{-i\beta x}-1\right)\right]c_{\mu 0}, \quad c_{-\mu}(x) = \left[\left(e^{-i\beta x}-e^{-i\beta L}\right) - \Gamma_1\left(e^{i\beta x}-e^{i\beta L}\right)\right]c_{\mu 0}, \tag{4}$$

where $c_{\mu 0} = -\dfrac{i\omega\mu_0}{N_\mu}\left[i\beta(1-\Gamma_1\Gamma_2) + 2s\dfrac{i\omega\mu_0}{N_\mu}\varphi_q |I_{\mu q}|^2\right]^{-1} I_{\mu q}^* \varphi_q \displaystyle\int_V (\mathbf{H}\cdot\mathbf{m}_q^*)dV$, $I_{\mu q} = \displaystyle\int_S (\mathbf{H}_{\mu 0}\cdot\mathbf{m}_q^*)dS$

and parameter s, depending on the line length, is given in [4] ($s \approx 2i\beta L^2$ for a special case βL<<1). Substituting (4) in (3) and using Ampere's law (an integration extends over an arbitrary contour C in the cross section yz which includes the strip)

$$\oint_C \mathbf{h}_\mu d\,\mathbf{l} = J(x),$$

one can find an induced electric dipole moment and using (2) - a magnetic dipole moment

$$\mathbf{p}_e = \frac{1}{i\omega}\mathbf{e}_x \int_0^L J(x)dx, \ \mathbf{p}_m = \sum_q c_q \int_V \mathbf{m}_q dV . \tag{5}$$

Polarizabilities can be written in a tensor form

$$\vec{\alpha}_{em} = A \cdot \begin{bmatrix} m_{qx}^* & m_{qy}^* & m_{qz}^* \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \; \vec{\alpha}_{mm} = B \cdot \begin{bmatrix} m_{qx} m_{qx}^* & m_{qx} m_{qy}^* & m_{qx} m_{qz}^* \\ m_{yx} m_{qx}^* & m_{qy} m_{qy}^* & m_{qy} m_{qz}^* \\ m_{qz} m_{qx}^* & m_{qz} m_{qy}^* & m_{qz} m_{qz}^* \end{bmatrix}, \tag{6}$$

where for the case $\beta L << 1$ coefficients A and B are the following

$$A = \frac{i}{6} \frac{\mu_0}{\sqrt{2WN_\mu}} \varphi_q I_{\mu q}^* V \beta^2 L^3 \left(-\beta + L \frac{\omega \mu_0}{N_\mu} \varphi_q \left| I_{\mu q} \right|^2 \right)^{-1}, \tag{7}$$

$$B = \varphi_q V^2 + \varphi_q^2 V^2 \left| I_{\mu q} \right|^2 \frac{\omega \mu_0 \beta^3 L^4}{3N_\mu} \left[i\beta(1 - \Gamma_1 \Gamma_2) + 2s\varphi_q \left| I_{\mu q} \right|^2 \frac{i\omega\mu_0}{N_\mu} \right]^{-1}, \tag{8}$$

and W is a characteristic impedance of a transmission line, which can be calculated as [5]

$$W = \frac{120}{\sqrt{\varepsilon}} \left(ln \frac{2{,}2L}{b} - 1 \right). \tag{9}$$

For a normally magnetized ferrite disk and a fundamental uniform mode of magnetization (when its components can be assumed to be $m_{qx} = 1$, $m_{qy} = -i$, $m_{qz} = 0$) calculated polarizability coefficients A (7) are shown in the Fig.2. Note that in this case an internal biasing magnetic field is uniform. The diameter of the resonator is taken equal to the length of a strip and the particle is characterized by the following set of parameters: L = 0.5mm, b = 20μm, $4\pi M_0$ = 1750 Oe, H_0 = 5320 Oe, $2\Delta H_0$ = 0.5 Oe, ε=10.

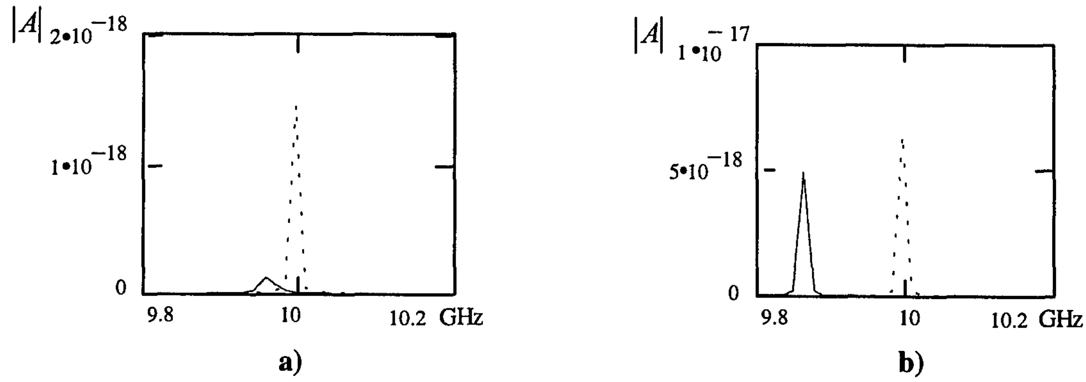

Fig. 2 Polarizability coefficient $|A|$ (ferrite film thickness: a) 10 μm, b) 50 μm). Solid curve: Self-consistent solution; Dotted: "Back" coupling neglected.

3. Calculation of Tensor Polarizabilities $\vec{\alpha}_{ee}$ and $\vec{\alpha}_{me}$

Tensor polarizabilities $\vec{\alpha}_{ee}$ and $\vec{\alpha}_{me}$ are calculated in the assumption that **H** = 0 in (1). A current distribution along a narrow strip in an external longitudinal electric field **E** is known from the antenna theory [5]

$$J(x) = J(L/2) f(x), \tag{10}$$

where $J(L/2) = \dfrac{2i\mathrm{E}}{\beta W \, cos(\beta L/2)} \left(1 - cos \dfrac{\beta L}{2} \right)$, $f(x) = \dfrac{cos\beta(x - L/2) - cos(\beta L/2)}{1 - cos(\beta L/2)}$. Induced electric dipole moment $\mathbf{p}_e$ is obtained by integrating the current $J(x)$ according (5). A magnetic dipole moment

$\mathbf{p}_m$ of the ferrite resonator is excited by the current (10) and can be calculated using (5) with the amplitude coefficients c_q being obtained from (2) for $\mathbf{H} = 0$. It can be easily seen that the magnetic field of the transmission line is related to the current as

$$\mathbf{h}_\mu = \frac{J(x)}{J_c}\mathbf{H}_{\mu 0}, \qquad (11)$$

where $J_c = \oint_C \mathbf{H}_{\mu 0} d\,\mathbf{l}$ (for this value the following relationship is valid $J_c = \sqrt{N_\mu / (2W)}$).

Performing calculations we come to the following polarizabilities for the case $\beta L \ll 1$

$$\ddot{\alpha}_{ee} = C \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \ddot{\alpha}_{me} = D \cdot \begin{bmatrix} \mathrm{m}_{qx} & 0 & 0 \\ \mathrm{m}_{qy} & 0 & 0 \\ \mathrm{m}_{qz} & 0 & 0 \end{bmatrix}, \qquad (12)$$

where $C = \frac{1}{6}\frac{\beta L^3}{\omega W}$, $D = \frac{i\beta L^3}{6W}\frac{\varphi_q I_{\mu q} V}{J_c}$.

4. Conclusion

Derived explicit expressions for polarizabilities show that all non-zero tensor elements, except $\ddot{\alpha}_{ee}$, have resonant character with resonance frequencies close, but not equal, to the MSW resonator eigenfrequencies. Elements of tensors of magnetoelectric coupling $\ddot{\alpha}_{em}$, $\ddot{\alpha}_{me}$ are proportional to the saturation magnetization M_0 of ferrite and to the third power of the strip length L^3 and increase with the growth of the resonator quality factor Q. For low magnetic losses these tensors are related as $\ddot{a}_{em} \approx \mu_0 \ddot{a}_{me}^{T*}$. Elements of the tensor $\ddot{\alpha}_{mm}$ are proportional to the resonator volume V. The tensor $\ddot{\alpha}_{ee}$ has no frequency dependence and is proportional to the third power of the strip length L^3. In the case when a ferrite resonator has a non-elliptic form (e.g., a straight-edge MSW resonator with a film of a rectangular form), calculations of polarizabilities must be carried out taking into account the influence of nonuniformity of the internal biasing magnetic field [6].

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